

The effect of early chemical freezeout on radial and elliptic flow from a full 3D hydrodynamic model*

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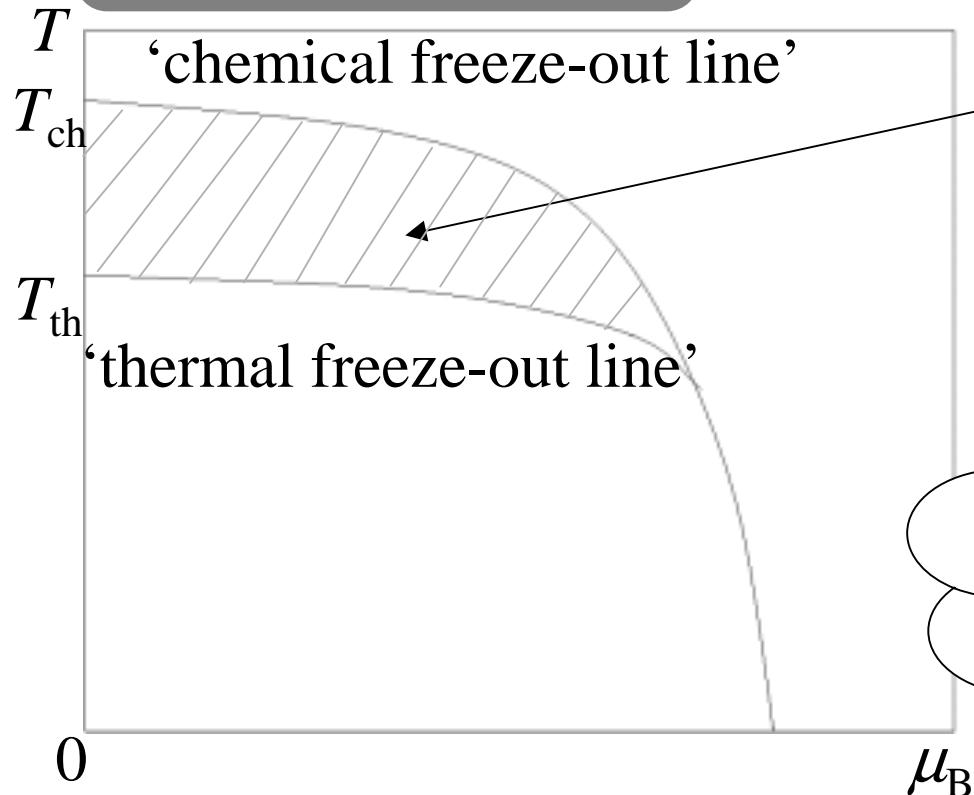
Contents:

- Introduction
- EOS of chemically non-equilibrium matter
- Hydrodynamic results
- p_t spectra & elliptic flow
- Summary

*In collaboration with
K. Tsuda (Waseda Univ.)

See also
T. Hirano, PRC**65**, 011901 (2002).
T. Hirano, PRL**86**, 2754 (2001).

Introduction



Chemically frozen
but
thermally equilibrated

We want to
describe this region
in terms of
hydrodynamics.

For studies of particle ratio at RHIC, see, e.g.,

- P.Braun-Munzinger *et al.*, Phys.Lett.B**518**(2001)41.
- W.Florkowski *et al.*, nucl-th/0106009.
- N.Xu and M.Kaneta, QM2001,(nucl-ex/0104021).
- D.Magestro, hep-ph/0112178.

OUR ROADMAP

Conventional Hydrodynamic Model

- Chemical & thermal equilibrium
- $T_{\text{ch}} = T_{\text{th}}$ ($\sim 100\text{-}140$ MeV)

← Today's talk

1st trial calculation

- $\mu_B = 0 \rightarrow$ Description at RHIC energies

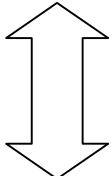
← Future work

Hydrodynamic Model in Next Generation

- Separate freeze-out temperature ($T_{\text{ch}} > T_{\text{th}}$)
- Including baryon & isospin chemical potentials
→ Detailed description of particle ratio & spectra at SPS and RHIC energies

Model EOS

- QGP phase (massless free u, d, s and g : $P=E/3$)
 - Mixed phase ($T_c=170$ MeV)
 - Hadron Phase
 - (All hadrons up to $\Delta(1232)$ are taken into account.)
- ❖ Model 1. Chemical Equilibrium (CE)



- ❖ Model 2. Chemically Frozen-Out (CFO)
- ❖ Model 3. Partial Chemical Equilibrium (PCE)

(1) Chemical Equilibrium (CE)

- A conventional resonance gas model in which both chemical and thermal equilibrium are assumed.
- All hadrons up to $\Delta(1232)$ are included.

$\pi, \eta, \rho, \omega, \eta', \phi(1020), f_0(980), a_0(980), h_1(1170), \sigma$

p, n

$\Delta(1232)$

K, K^*

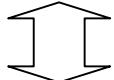
Λ

Σ

- Effects of excluded volume correction are neglected.

(2) Chemically Frozen-Out (CFO) EOS

Conservation of particle number $\partial_\mu \hat{n}_i^\mu = 0$



Introduce **chemical potentials** μ_i associated with n_i

How to determine $\mu_i(T; T_{\text{ch}})$

From the conservation of entropy $\partial_\mu s^\mu = 0$,

$$\frac{n_i(T < T_{\text{ch}})}{s(T < T_{\text{ch}})} = \frac{n_i(T_{\text{ch}})}{s(T_{\text{ch}})}$$

for all species along the adiabatic path.

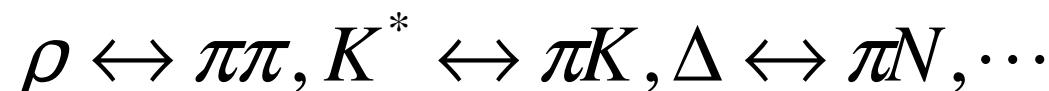
Here we assume T_{ch} ($= T_c$) = 170 MeV for simplicity.

(3) Partial Chemical Equilibrium (PCE)*

Conserved number: (direct + resonance decays) at $T=T_{\text{ch}}$

$$\bar{n}_\pi = n_\pi + \sum_{i \neq \pi} d_i n_i, \bar{n}_K = n_K + \sum_{i \neq K} d_i n_i, \dots$$

Even below T_{ch} , some strong interactions can be equilibrated with keeping $\bar{n}_\pi(T)/s(T) = \bar{n}_\pi(T_{\text{ch}})/s(T_{\text{ch}}), \dots$



$$\mu_\rho = 2\mu_\pi, \mu_{K^*} = \mu_\pi + \mu_K, \mu_\Delta = \mu_\pi + \mu_N, \dots$$

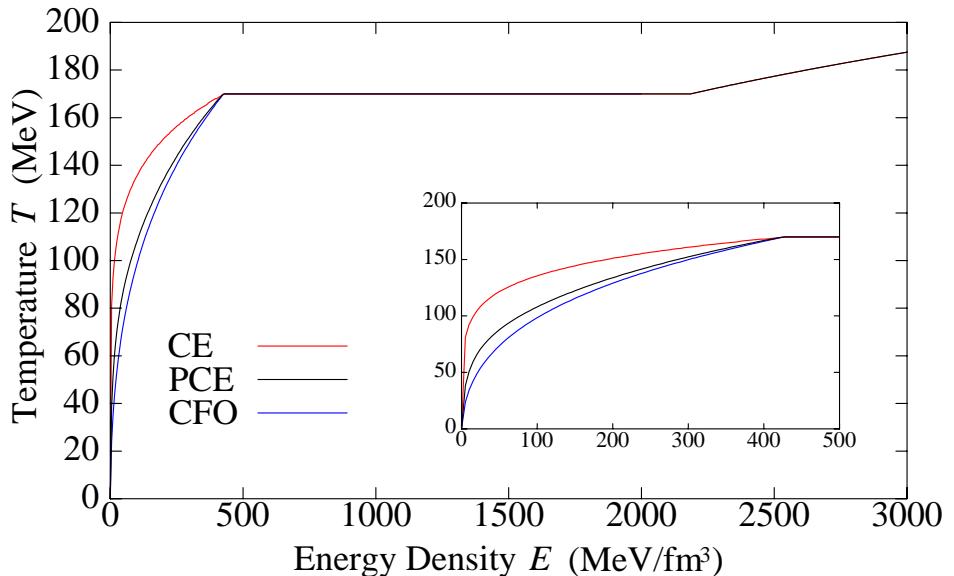
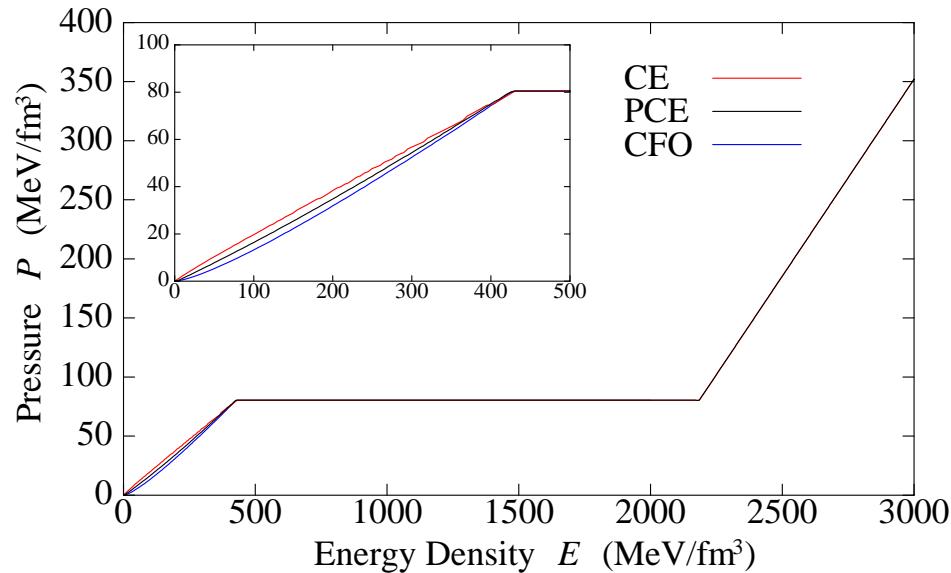
All chemical potentials are written in

$$\mu_\pi, \mu_K, \mu_\eta, \mu_N, \mu_\Lambda \text{ and } \mu_\Sigma$$

(*See, for example, H.Bebie *et al.*, Nucl.Phys.**B378**(1992)95.)

Equation of State

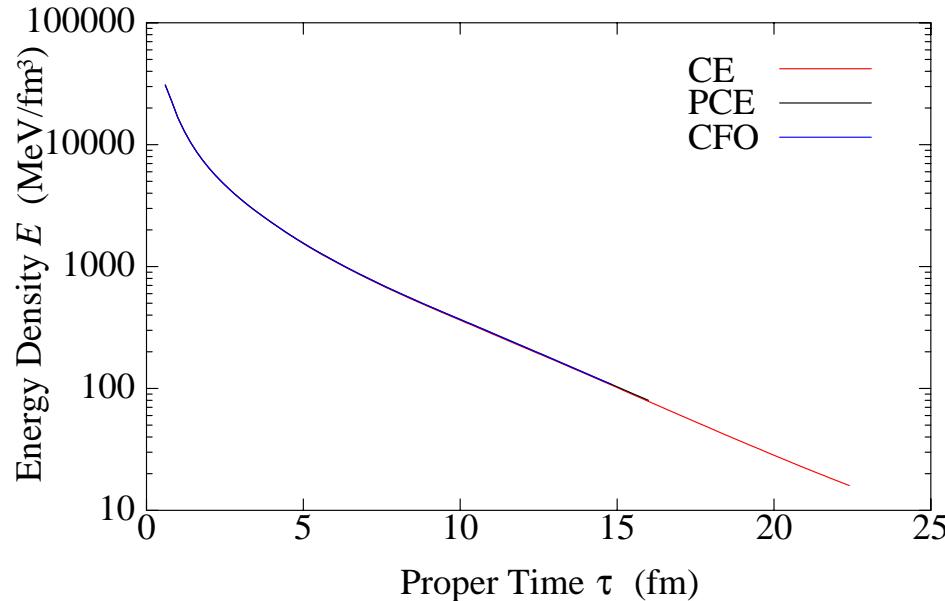
CE: Chemical Equilibrium
PCE: Partial Chemical Equilibrium
CFO: Chemically Frozen-Out



Three models
are very similar
to each other.

- Larger E in PCE and CFO at a fixed T than in CE due to large fraction of resonances
 - PCE looks like CFO rather than CE.

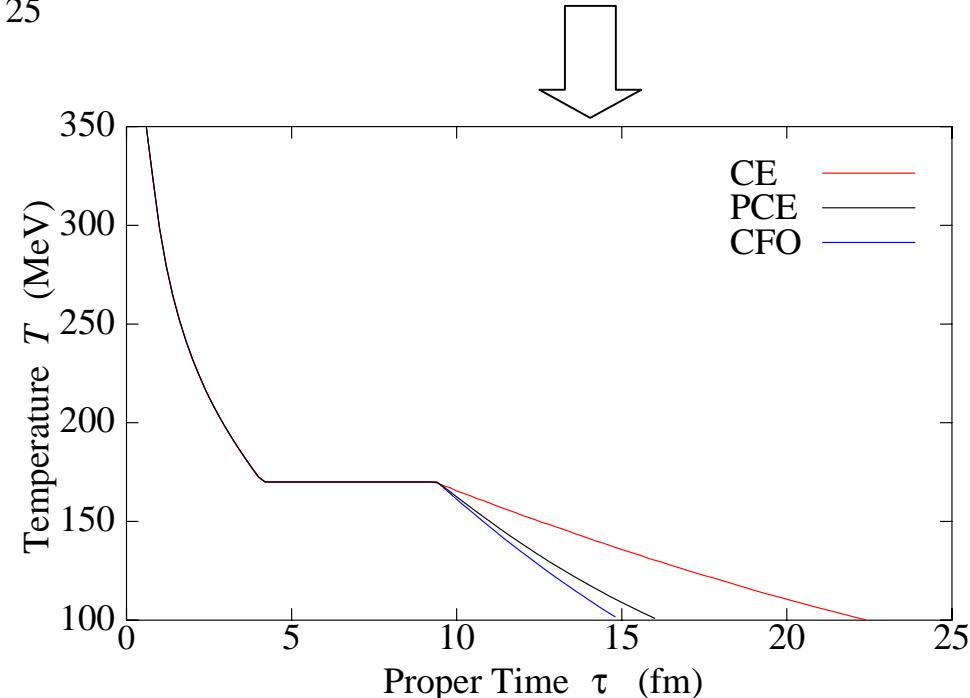
Time Evolution of E and T



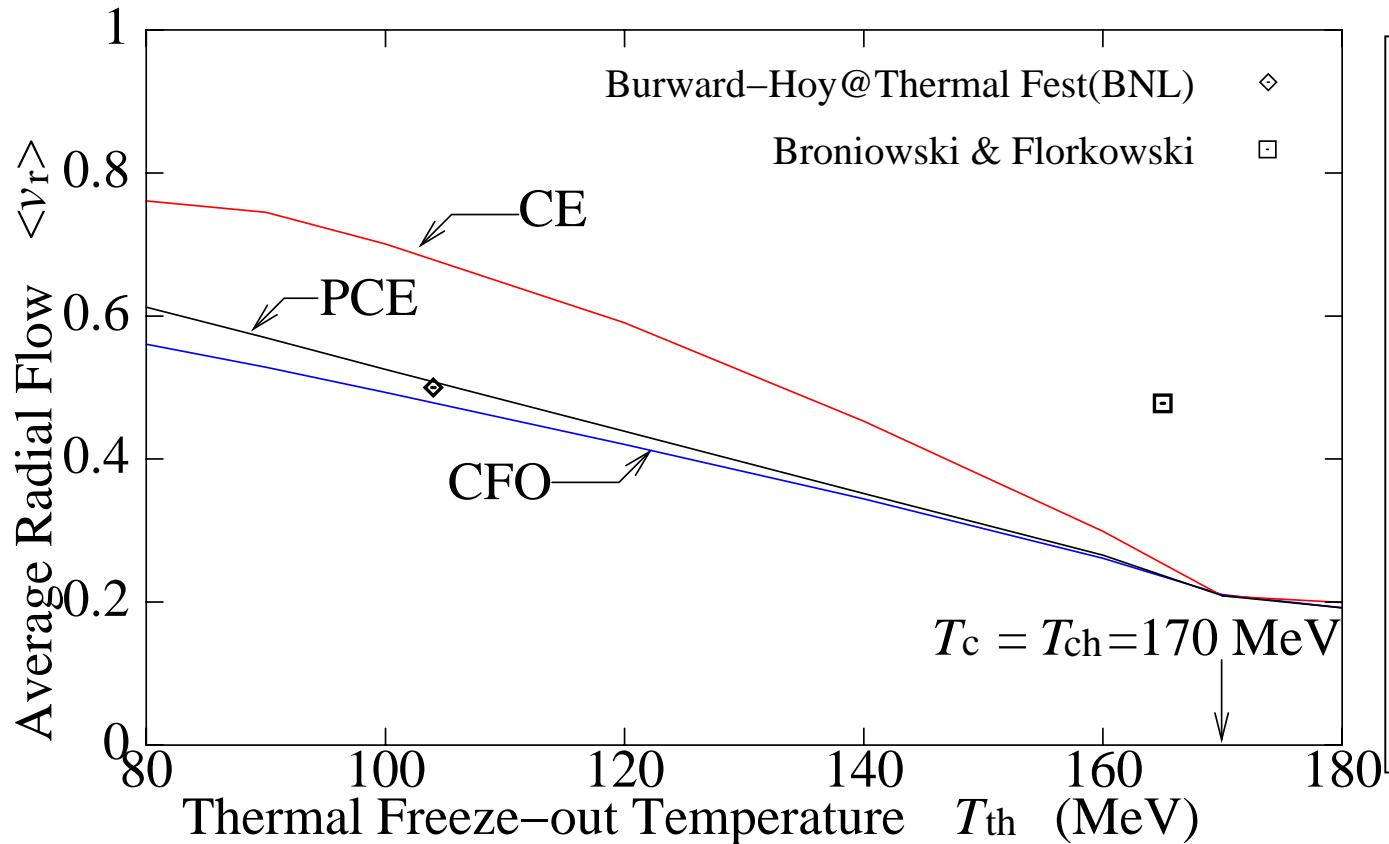
We cannot distinguish
between three models !

Initial condition for central collisions
at the RHIC energy:
 $\tau_0=0.6$ fm, $b=2.4$ fm
 $E_0=28.9$ GeV/fm 3 , $T_0=349.5$ MeV

But, CFO and PCE have
shorter lifetimes than CE.



T_{th} vs. $\langle v_r \rangle$ from hydrodynamics

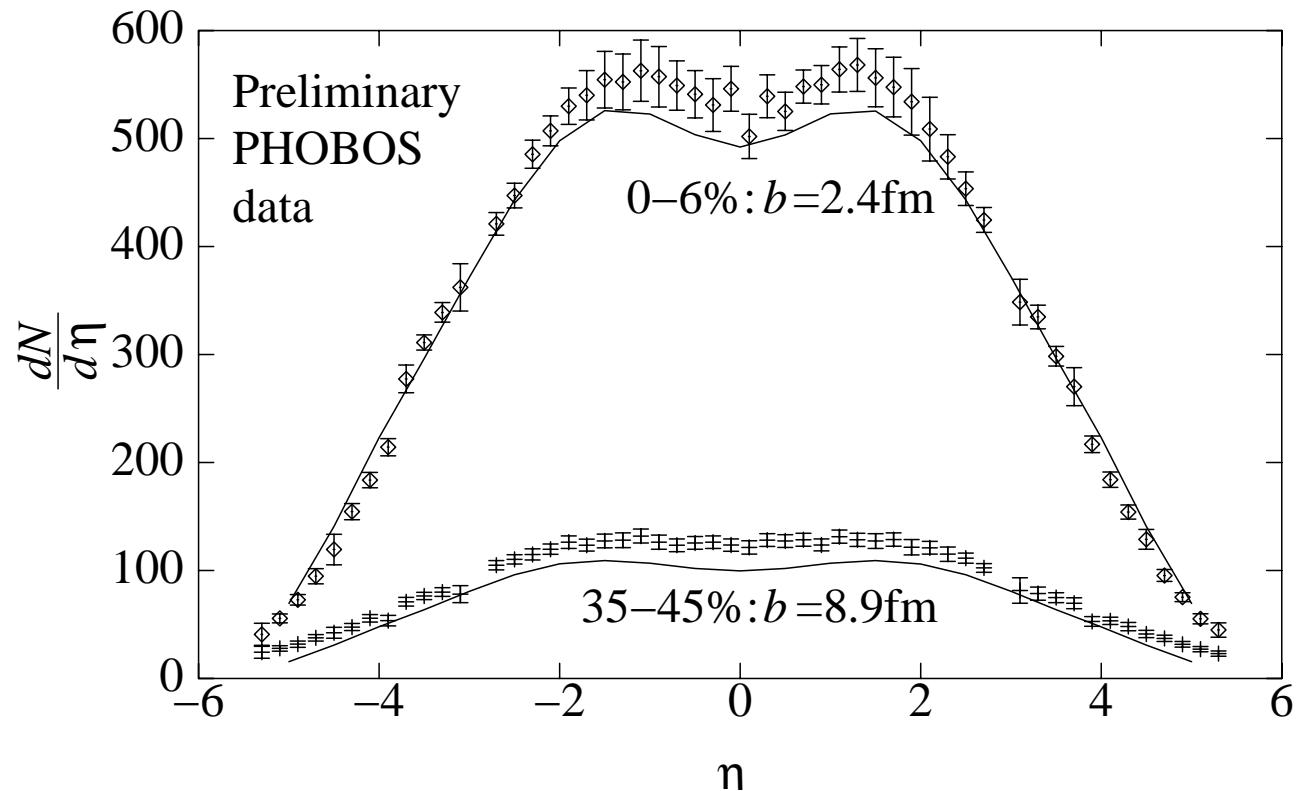


• **J.Burward-Hoy**
Talk at Thermal Fest (BNL)
Hydrodynamics-based
fitting for π , K and p
in low pt region
Resonance decays are **not**
included.

• **Broniowski & Florkowski**
PRL87,272302(2001).
Another parameterization
 $T_{\text{th}}=T_{\text{ch}}$ is assumed.
Resonance decays are
included.

More detailed analyses with both hydro and thermal models
are needed for understanding **thermal** freeze-out.

Pseudorapidity Distribution of Charged Particles in Au+Au 130 A GeV



PCE: $T_f = 140 \text{ MeV}$

Initial condition:

$$\tau_0 = 0.6 \text{ fm}$$

$$E_0 = 28.9 \text{ GeV/fm}^3$$

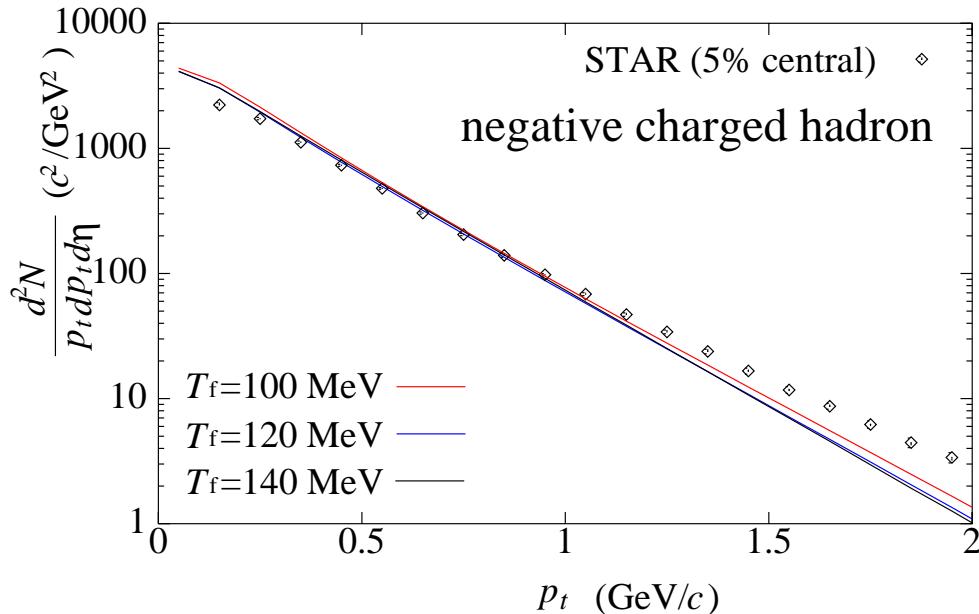
$$T_0 = 349.5 \text{ MeV}$$



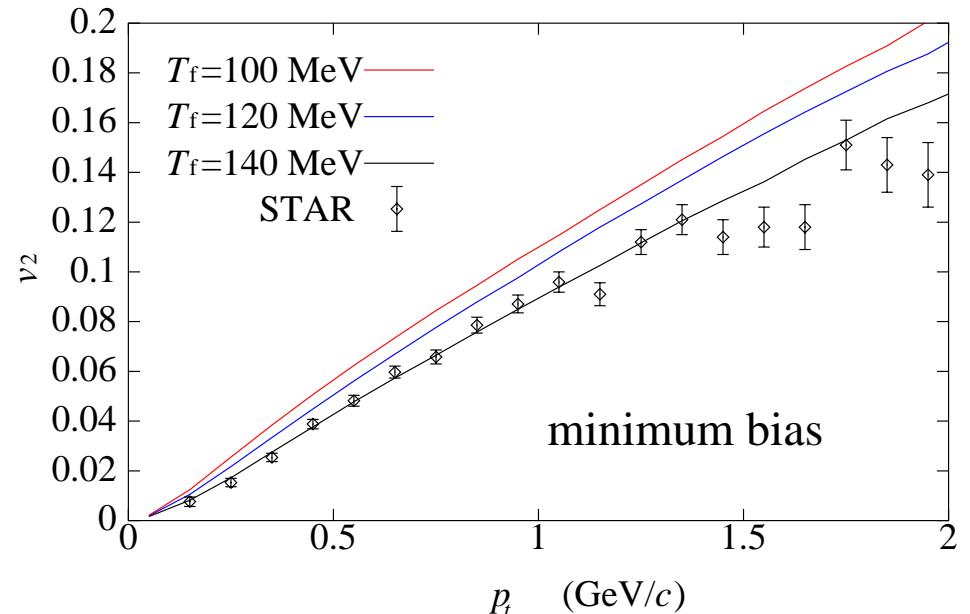
For initial transverse and longitudinal profiles, see
T. Hirano, PRC65,011901(2002).

Data: PHOBOS Collaboration, QM2001.

p_t spectrum & $v_2(p_t)$ of Charged Particles in Au+Au 130 A GeV



Almost independent of T_f



Smaller T_f , larger v_2

- Our results with $T_f \sim 140 \text{ MeV}$ are consistent with experimental data of both p_t spectrum and $v_2(p_t)$ below $1 \text{ GeV}/c$.
- Contribution from hard processes can be dominated above $1 \text{ GeV}/c$.

Data: STAR, PRL87, 112303(2001) & PRL86, 402(2001).

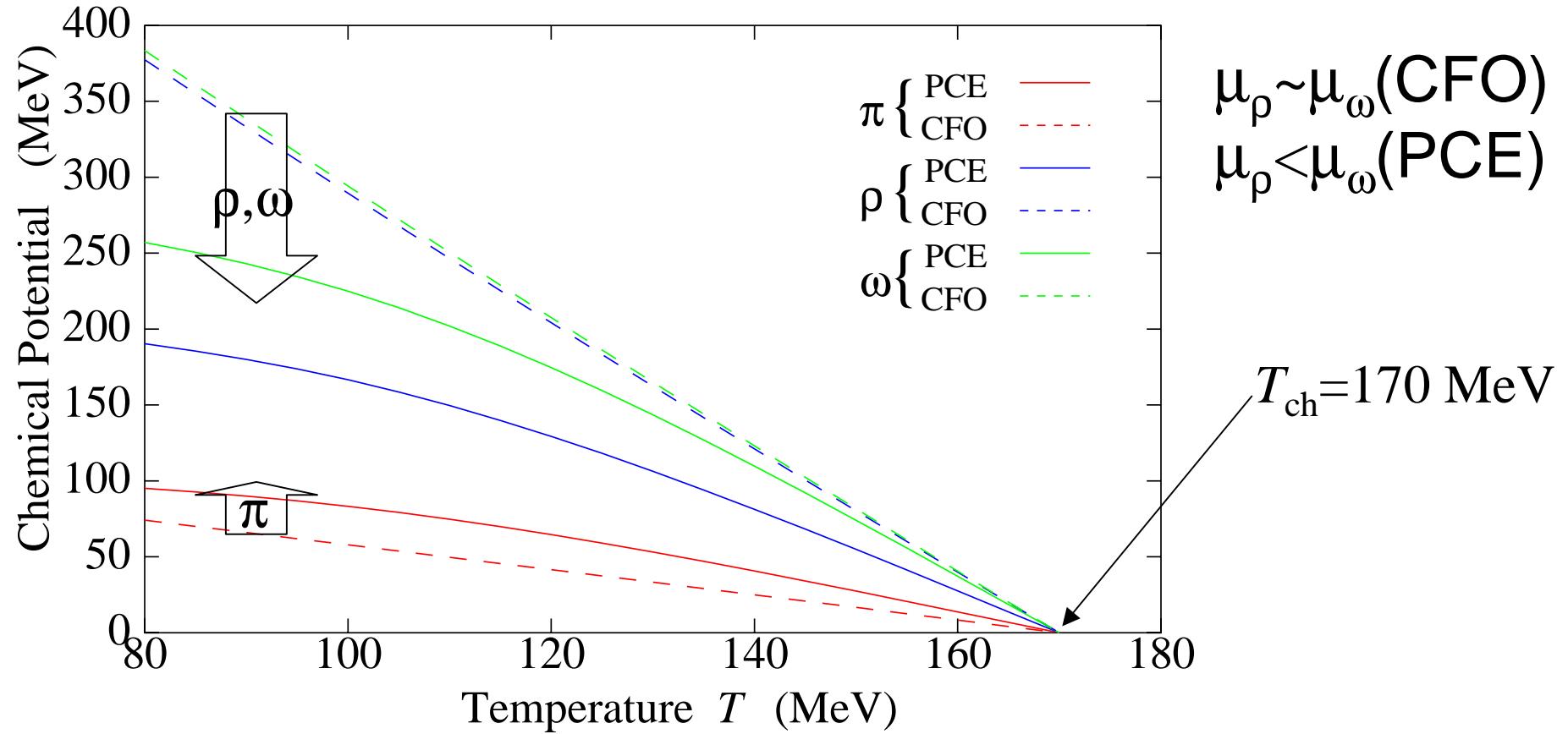
Summary

- Hydrodynamic model with chemically non-equilibrium EOS
- In comparison with conventional EOS (chemical equilibrium),
the system cools down more rapidly.
radial and elliptic flow are slightly suppressed.
- $T_f \sim 140$ MeV and $\langle v_r \rangle \sim 0.35$ are consistent with experimental data.

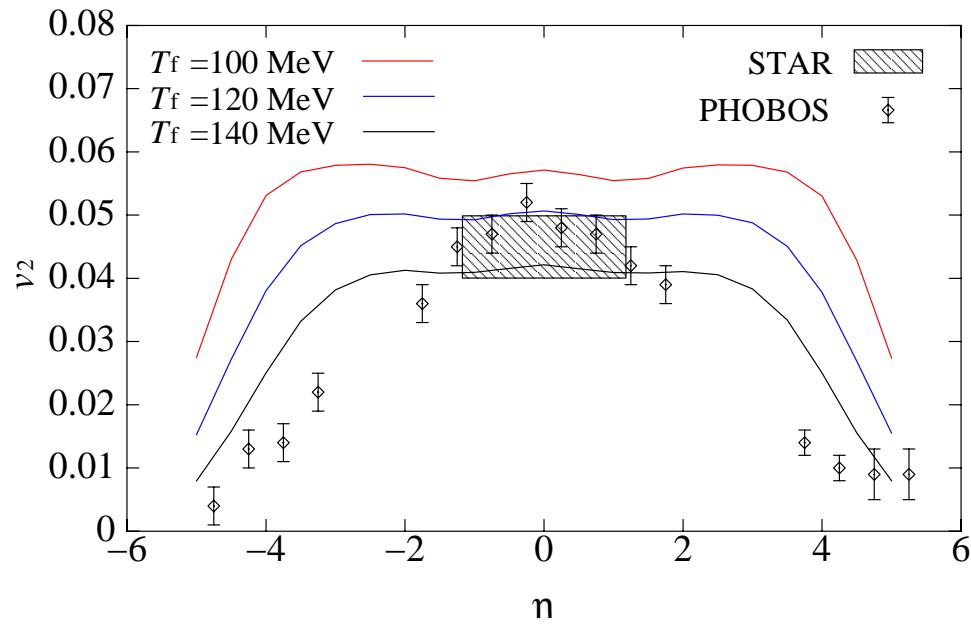
Future Works

- Baryonic chemical potential must be included (work in progress).
- Detailed analyses of ratio & spectra at various collision energies
are needed in terms of this model.
- The effect on HBT radii due to small lifetime of fluid ?
- Hydro(soft) + high p_t (hard) model ?

Chemical Potentials as Functions of T

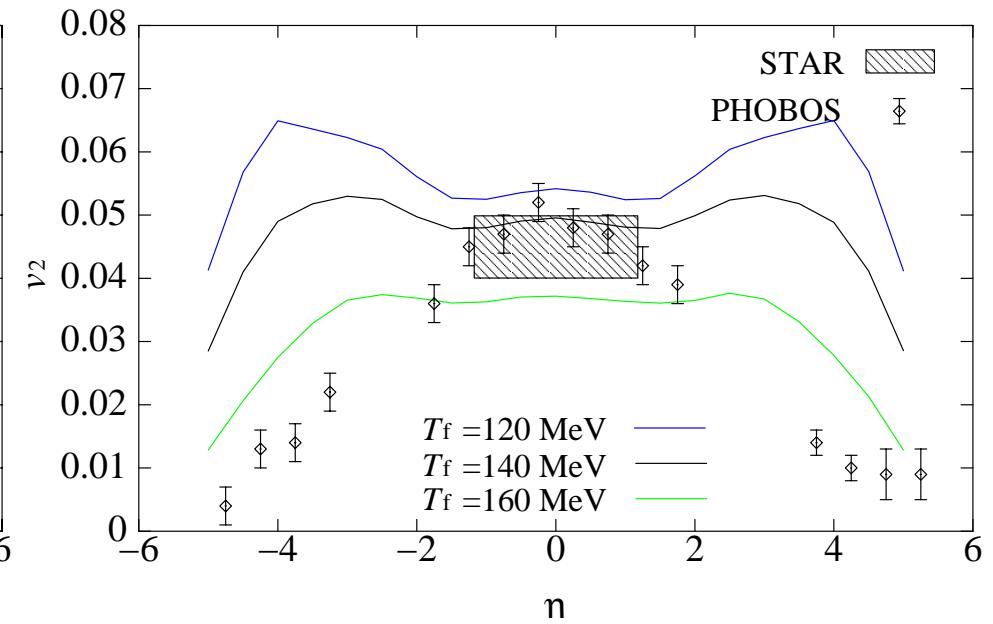


$v_2(\eta)$ of Charged Particles in Au+Au 130 A GeV



PCE

v_2 is almost flat in $-2 < \eta < 2$.



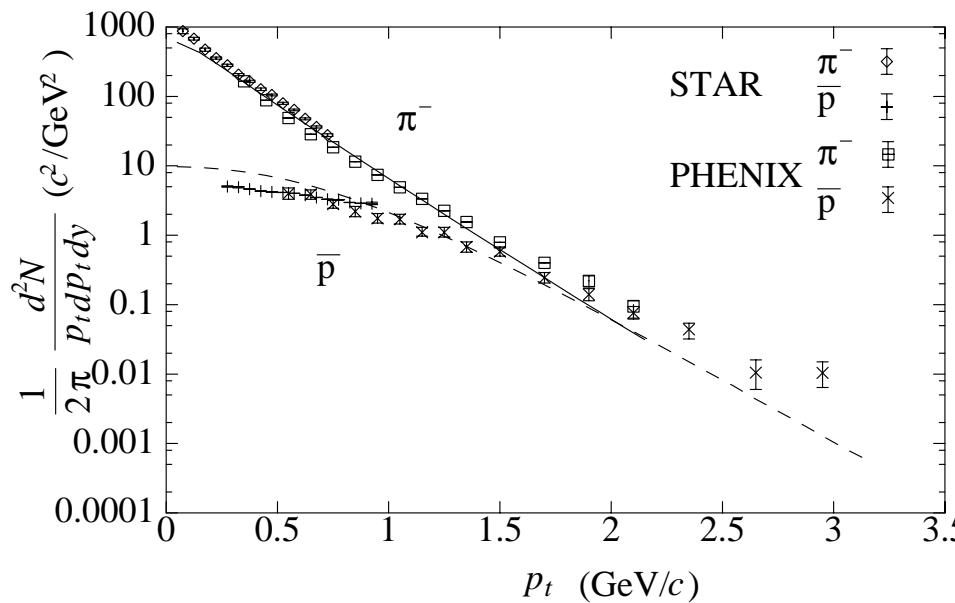
CE

Is early thermalization achieved only near midrapidity ?
 → See, e.g., T.Hirano, PRC65,011901(2002).

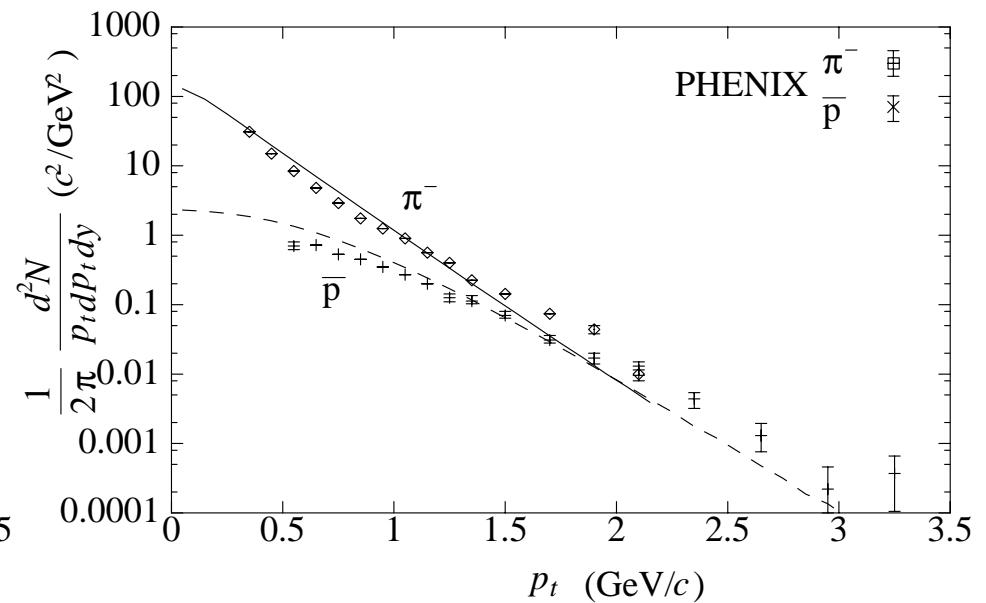
p_t Distribution of π and \bar{p} in Central and Semi-Central Au+Au 130 A GeV

PCE: $T_f=140$ MeV

central



semi-central

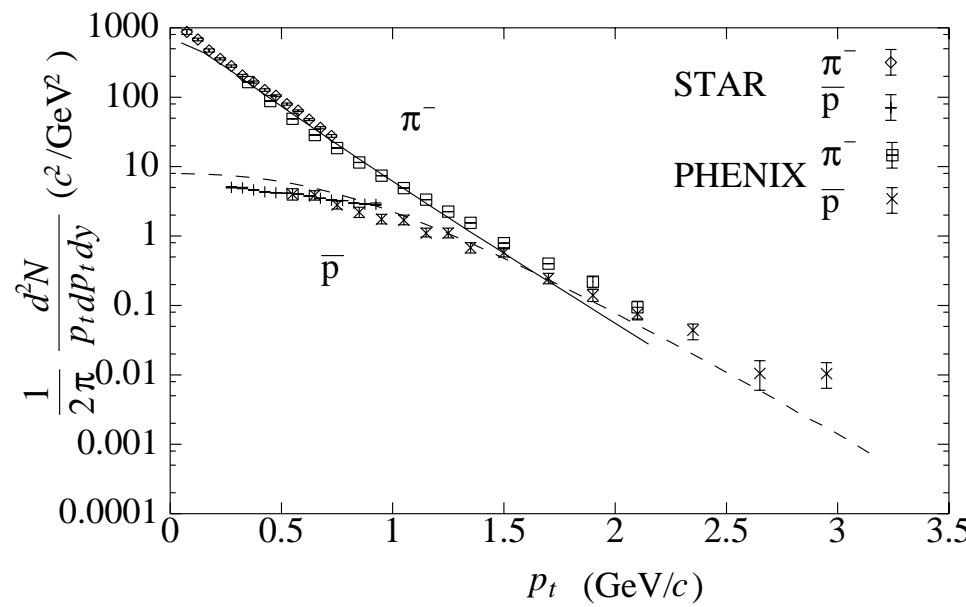


STAR: PRL87, 262302(2001) & nucl-ex/0111004.
PHENIX: nucl-ex/010512.

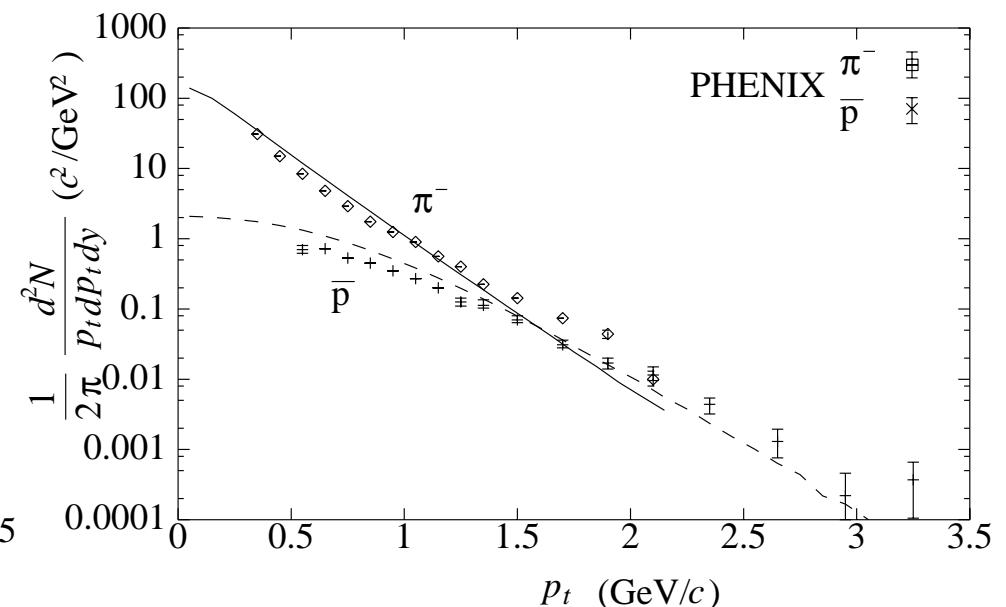
p_t Distribution of π and \bar{p} in Central and Semi-Central Au+Au 130 A GeV

PCE: $T_f=120$ MeV

central



semi-central

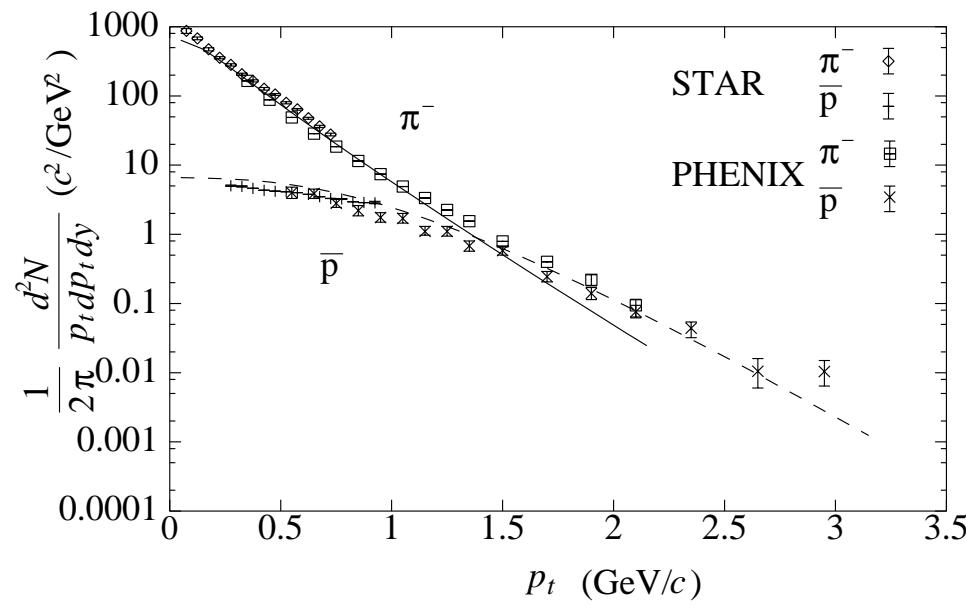


STAR: PRL87, 262302(2001) & nucl-ex/0111004.
PHENIX: nucl-ex/010512.

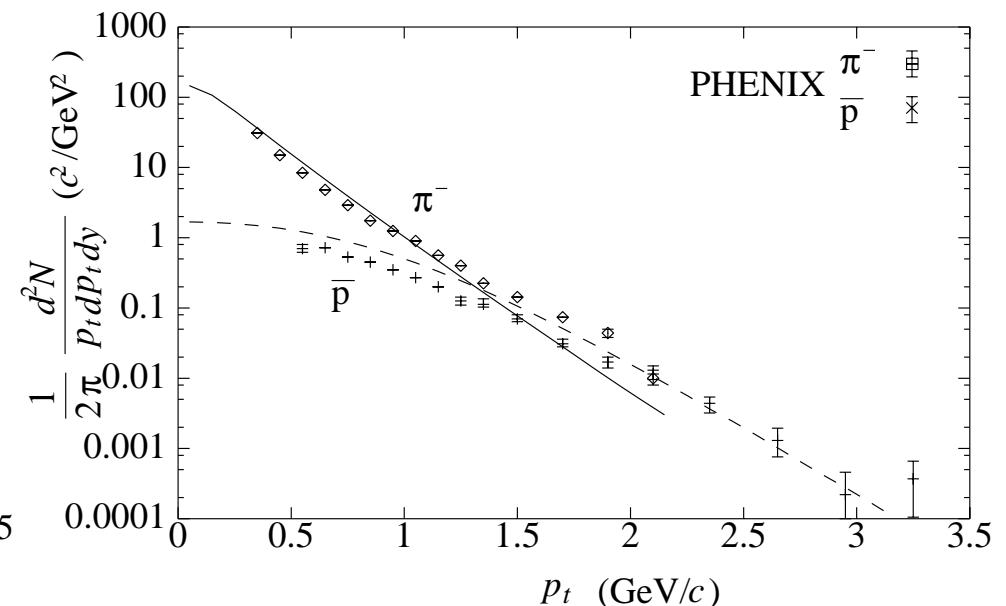
p_t Distribution of π and \bar{p} in Central and Semi-Central Au+Au 130 A GeV

PCE: $T_f=100$ MeV

central



semi-central

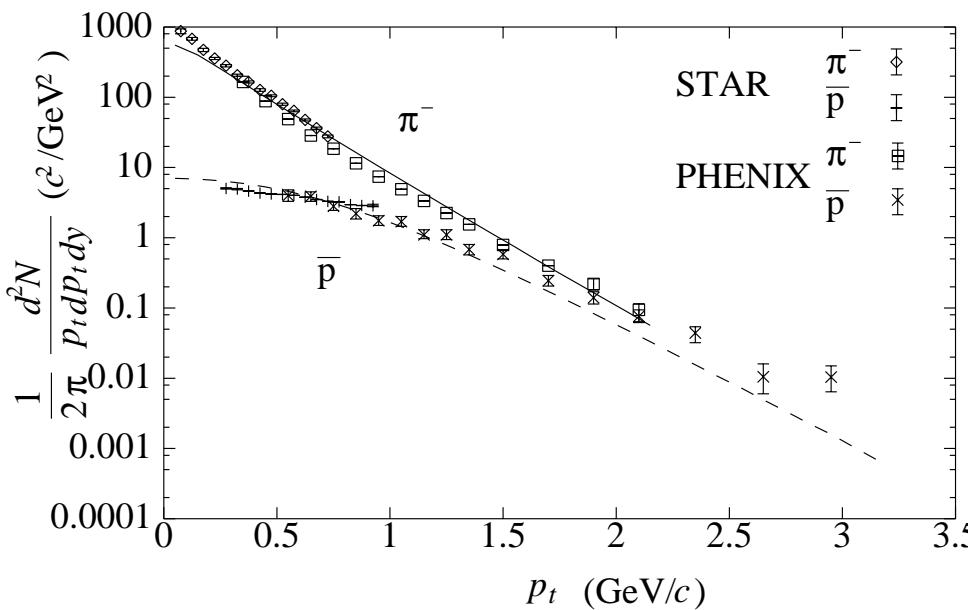


STAR: PRL87, 262302(2001) & nucl-ex/0111004.
PHENIX: nucl-ex/010512.

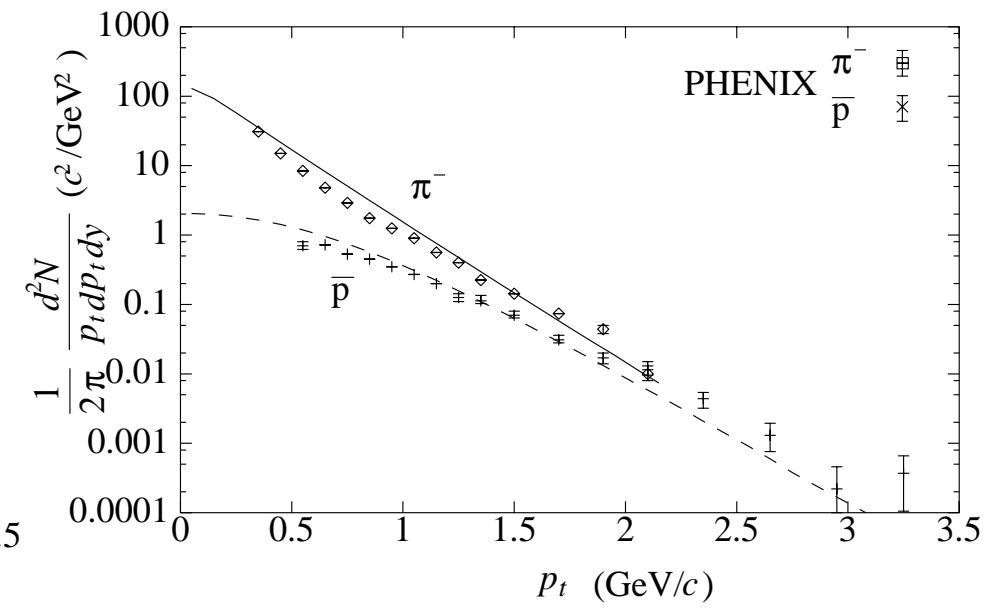
p_t Distribution of π and \bar{p} in Central and Semi-Central Au+Au 130 A GeV

CE: $T_f=160$ MeV

central



semi-central

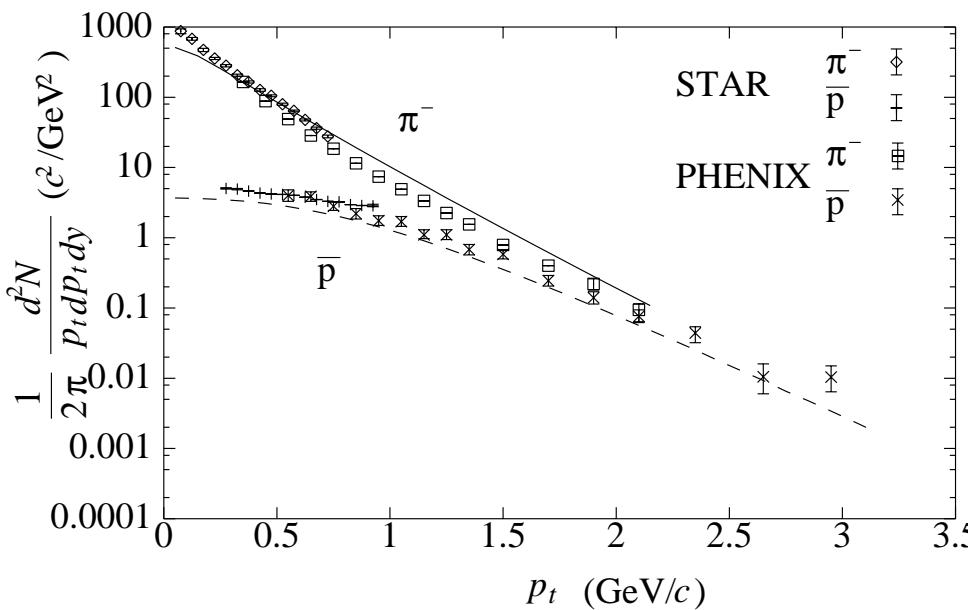


STAR: PRL87, 262302(2001) & nucl-ex/0111004.
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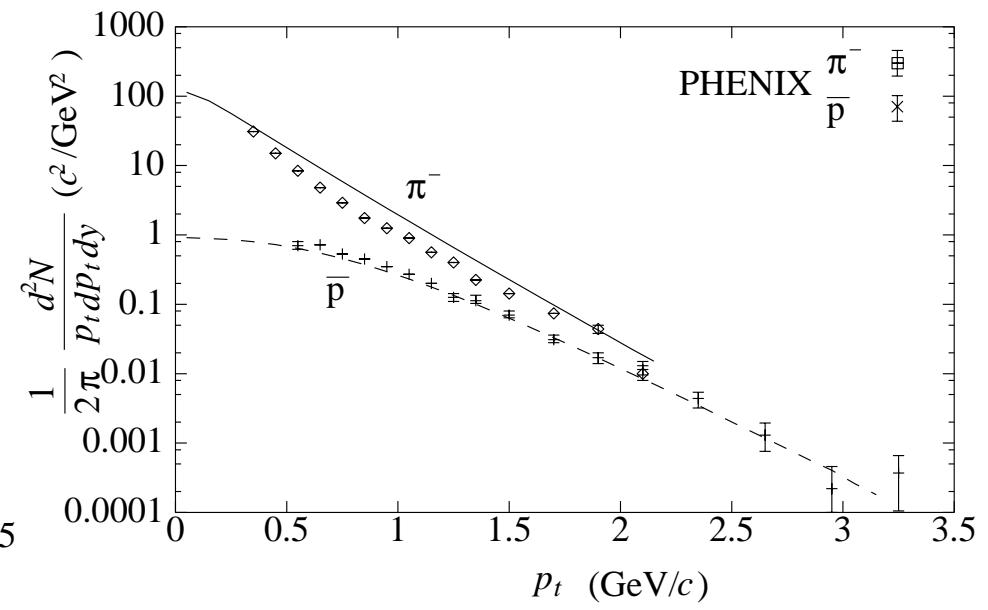
p_t Distribution of π and \bar{p} in Central and Semi-Central Au+Au 130 A GeV

CE: $T_f=140$ MeV

central



semi-central

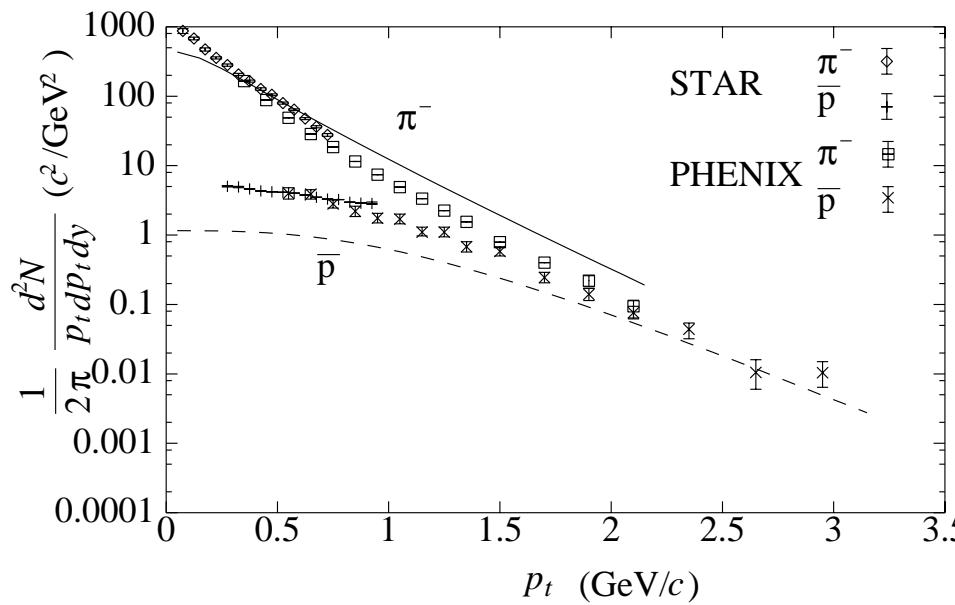


STAR: PRL87, 262302(2001) & nucl-ex/0111004.
PHENIX: nucl-ex/010512.

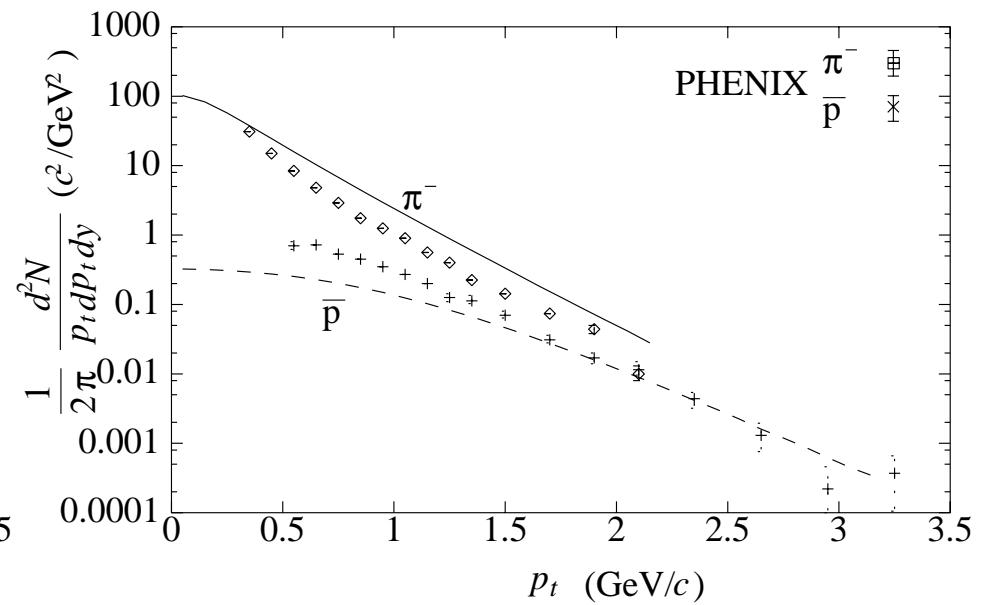
p_t Distribution of π and \bar{p} in Central and Semi-Central Au+Au 130 A GeV

CE: $T_f=120$ MeV

central

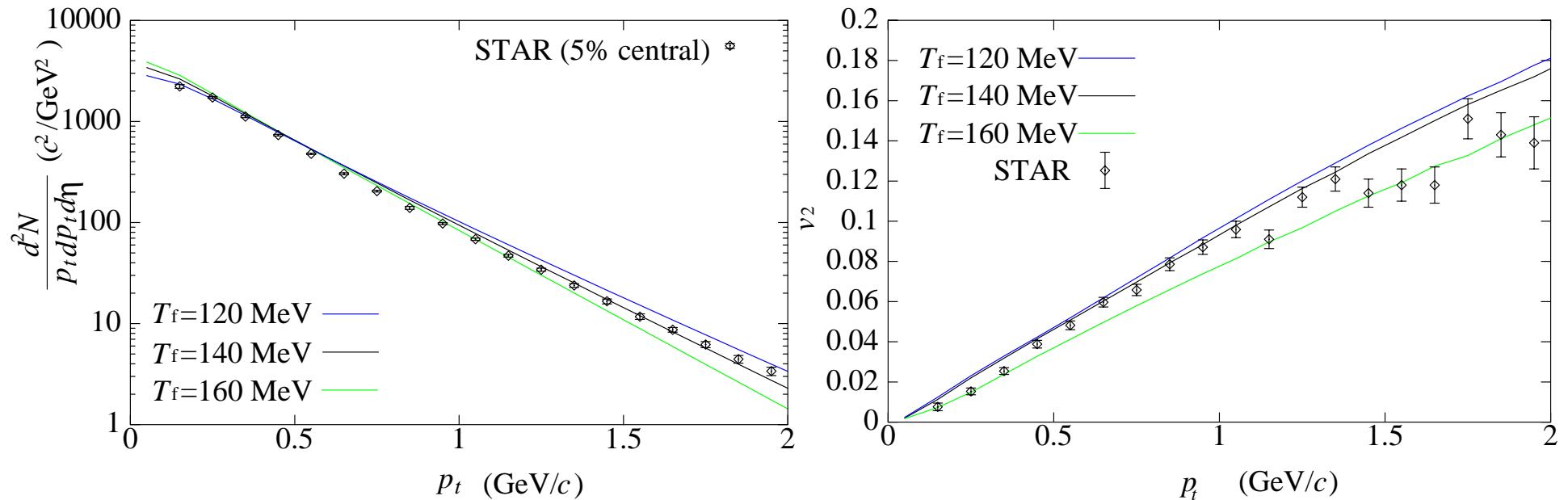
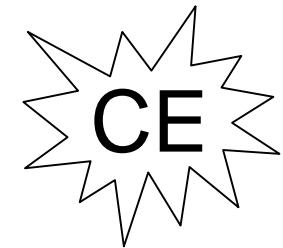


semi-central



STAR: PRL87, 262302(2001) & nucl-ex/0111004.
PHENIX: nucl-ex/010512.

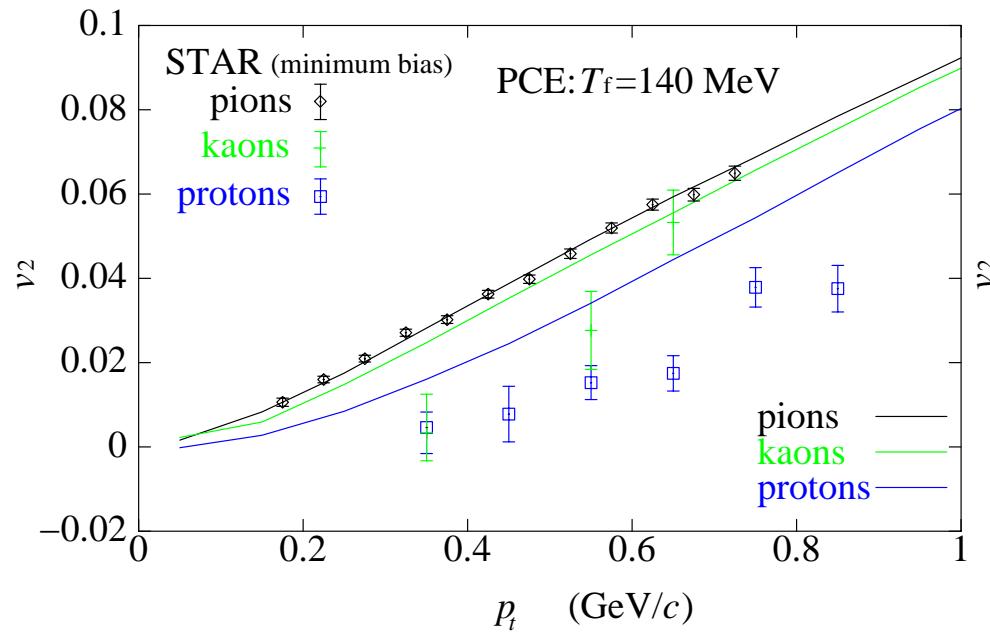
p_t spectrum & $v_2(p_t)$ of Charged Particles in Au+Au 130 A GeV



Our results with $T_f \sim 140$ MeV in model CE are consistent with the work by Kolb *et al.*
(P.F.Kolb *et al.*, Phys.Lett.B500(2001)232.)

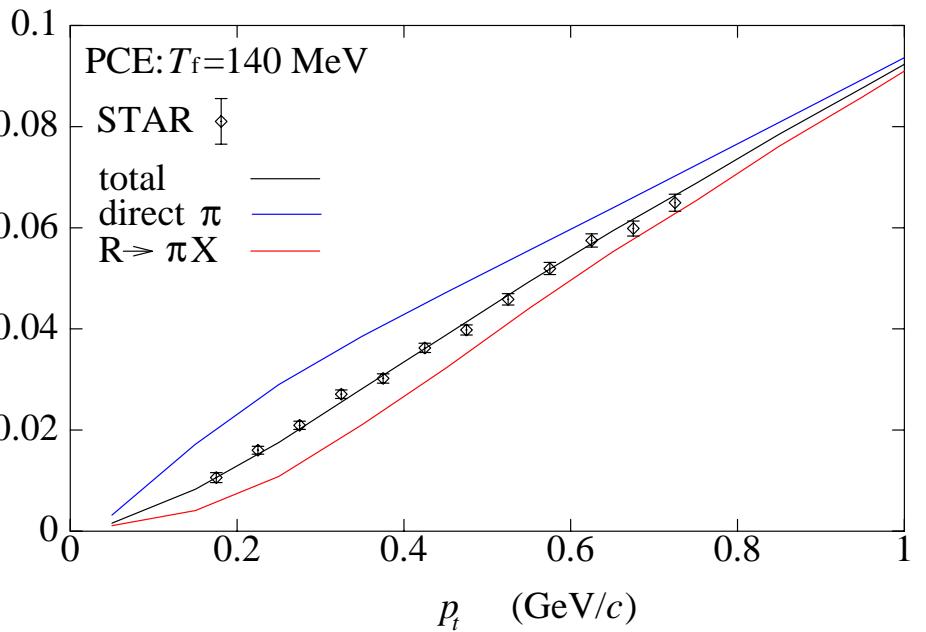
Data: STAR, PRL87, 112303(2001) & PRL86, 402(2001).

$v_2(p_t)$ for identified particles and reduction due to resonance decays



Pions \rightarrow Good!
Kaons and protons \rightarrow ???

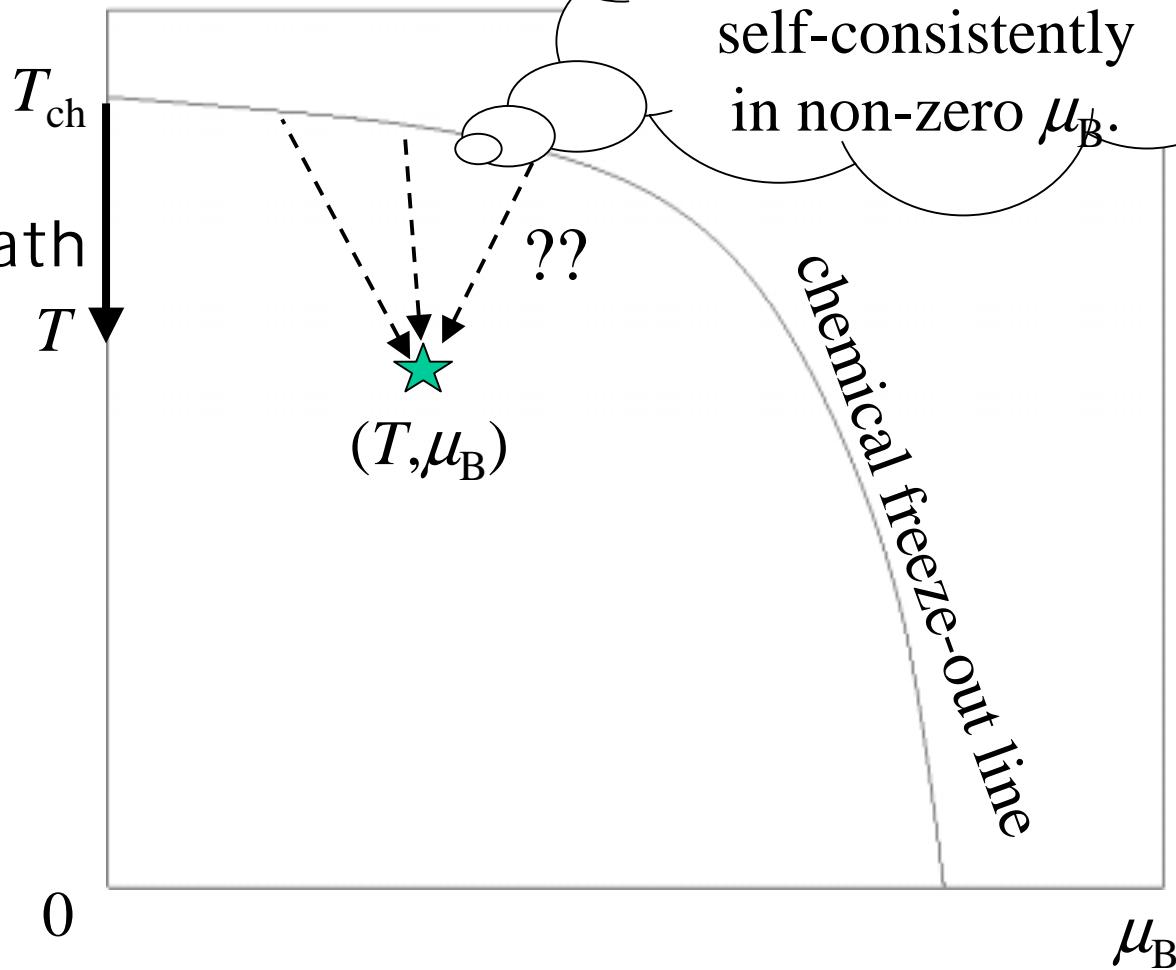
Data: STAR, PRL87, 182301(2001)



Reduction of v_2 due to decays
of resonance after thermal
freeze-out
 \rightarrow T.Hirano, PRL86, 2754(2001).

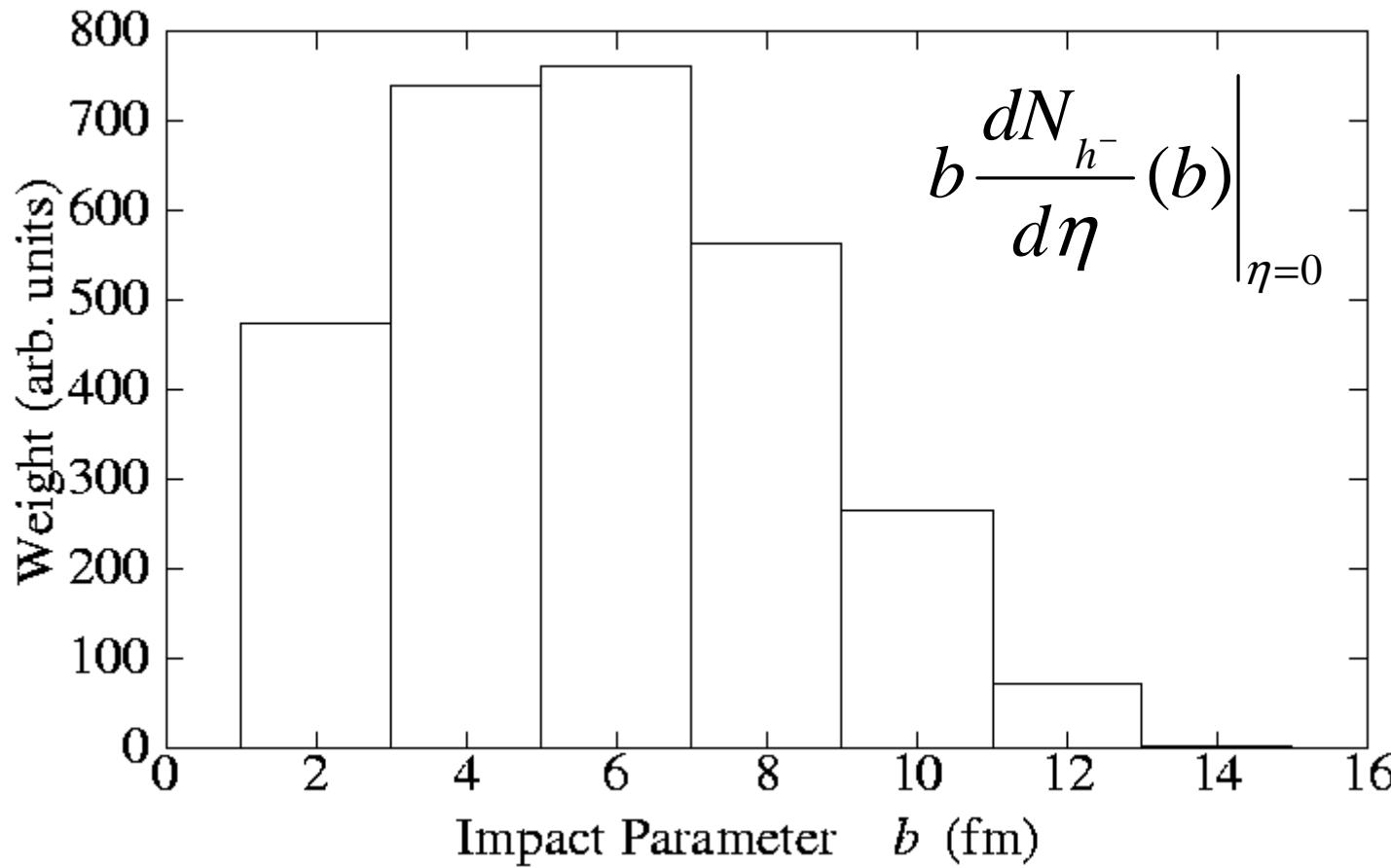
EOS with $\mu_B \neq 0$

Trivial
adiabatic path
in $\mu_B=0$



The adiabatic path
itself must be
determined
self-consistently
in non-zero μ_B .

Impact Parameter Dependence of Weight for Minimum Bias Data



$$b \frac{dN_{h^-}}{d\eta}(b) \Big|_{\eta=0}$$

PCE: $T_f = 140$ MeV